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PRESTO VERSION DELTA

PROGRAM FOR RAPID EARTH-TO-SPACE TRAJECTORY OPTIMIZATION

by Richard C. Rosenbaum, Robert E. Willwerth, Jr., and Richard L. Moll

Prepared by
LOCKHEED MISSILES & SPACE COMPANY
Sunnyvale, Calif.
for Langley Research Center

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FOREWORD

This report was prepared by the Aerospace Sciences Laboratory of the Lockheed Missiles and Space Company, Palo Alto, California. It presents documentation for a modification of the digital computer Program for Rapid Earth-to-Space Trajectory Optimization (PRESTO). The original program was developed by Lockheed for Langley Research Center under Contract NAS 1-2678,* and the present work was funded as Task I of Contract NAS 1-5255. This report is in the form of an addendum to the final report of the initial contract. A FORTRAN source listing and deck included with a master copy of this report complete the program documentation. Dr. R. C. Rosenbaum was responsible for the present contract, with major contributions by R. E. Willwerth and R. L. Moll.

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* Results of the program carried out under Contract No. NAS 1-2678 have been published as NASA CR-158 entitled "Program for Rapid Earth-to-Space Trajectory Optimization" by Robert E. Willwerth, Jr., Richard C. Rosenbaum, and Wong Chuck.

PRESTO VERSION DELTA

PROGRAM FOR RAPID EARTH-TO-SPACE TRAJECTORY OPTIMIZATION

ABSTRACT

This report presents documentation for modifications to the current trajectory optimization program known as PRESTO which was developed for NASA Langley Research Center. These modifications reduce the core storage requirements and improve the computational speed of the PRESTO program. The modified program is called the PRESTO VERSION DELTA.

SUMMARY

One of the primary objectives in the development of PRESTO was computational speed for the sake of economy. This objective was largely accomplished, with run times of one to two minutes for a complete trajectory optimization. However, when the computation facility at Langley Research Center converted from the use of FORTRAN II to FORTRAN IV, a loss occurred of approximately 4000 cells of computer core storage available to all programs. For PRESTO, this forced a recoding into a "chain-link" format with a resultant loss in computing speed and economy. This report documents modifications to PRESTO which restore much of the original speed and/or will provide additional core storage for flexibility in future additions and modifications. The resultant program is called the PRESTO Delta deck.

The increased computational speed was accomplished through a variety of programming improvements which reduce the size of PRESTO by more than 2100 cells. This will allow a more efficient chain-link arrangement than is now possible. However, independent of any chain-link improvements, the Delta deck in FORTRAN II is at least ten percent faster than the original PRESTO. In addition, various other improvements have been included. The most important of these is a change in the computation of coast trajectories which increases numerical accuracy and thereby improves the convergence pattern.

PROGRAM MODIFICATIONS

Reduction in Size

The two types of modification which produced major savings in program size involved renumbering of the variables of integration so that all matrix operations can use "DO loops" instead of individual statements. The first of these is in the adjoint equations. In each set the order of the λ_m and λ_T has been reversed so that the sequence is the same as the trajectory variables. Further, each set of adjoint variables is now consistently grouped, as indicated on the following page.

The second type of renumbering is in the integration of the $(\Lambda\ W^{-1}\ \Lambda^T)$ terms for the EI matrix. A "floating" numbering system has been incorporated such that the EI terms in integration directly follow the adjoint variables regardless of the number of constraints being used. In this way, there is always only one group of integration variables.

The subroutines which are affected by these changes are TRAJ, DEQ, MEQ, RKAD, and the MAIN program. In addition, subroutines ICS and OPTION have been partially recoded for reduced size. Finally, the LUNEPH and MAIN have been reduced in size through use of the DATA statement which is available in FORTRAN IV for loading constants.

The following two pages define the new numbering of the variables of integration. The associated changes in coding are self-explanatory when reading the source program. The form of the data input and answer output is unchanged by the above modifications. As described in the next section, however, there is one change in input required by the new coast computation.

PRESTO VERSION DELTA

VARIABLES OF INTEGRATION

X (1)	=	V	(Velocity)
X (2)	=	GAM	(Flight path angle)
X (3)	=	R	(Radius)
X (4)	=	M	(Mass)
X (5)	=	TAU	(Longitude)
X (6)	=	PSI	(Azimuth)
X (7)	=	LAM	(Latitude)
X (8)	=	LV1	(Adjoint Variables)
X (9)	=	LG1	.
X (10)	=	LR1	.
X (11)	=	LM1	.
X (12)	=	LP1	
X (13)	=	LL1	
X (14)	=	LV2 or EI11 for 1 constraint	
X (15)	=	LG2	
X (16)	=	LR2	
X (17)	=	LM2	
X (18)	=	LP2	
X (19)	=	LL2	
X (20)	=	LV3 or EI11 for 2 constraints	
X (21)	=	LG3 or EI12 for 2 constraints	
X (22)	=	LR3 or EI22 for 2 constraints	

X (23) = LM3

X (24) = LP3

X (25) = LL3

X (26) = LV4 or EI11 for 3 constraints

X (27) = LG4 or EI12 for 3 constraints

X (28) = LR4 etc.

X (29) = LM4

X (30) = LP4

X (31) = LL4

X (32) = LV5 or EI11 for 4 constraints

X (33) = LG5 or EI12 for 4 constraints

X (34) = LR5 etc.

X (35) = LM5

X (36) = LP5

X (37) = LL5

X (38) = LV6 or EI11 for 5 constraints

X (39) = LG6 or EI12 for 5 constraints

X (40) = LR6 etc.

X (41) = LM6

X (42) = LP6

X (43) = LL6

X (44) = EI11 for 6 constraints

X (45) = EI12

X (46) = EI22

X (47) = EI13

X (48) = EI23

X (49) = EI33

X (50) = EI14

CHANGE IN INDEPENDENT VARIABLE ACROSS CLOSED-FORM COASTS

The independent variable for the coast stages has been changed from angle to time. This change, together with a new equation for coast time, improves program convergence when coast and burn times are being optimized.

This change in independent variable changes the calculation for the discontinuity in the adjoint variables across the coast. One must now obtain partial derivatives across a coast with a fixed time rather than a fixed angle. The closed-form coast equations, however, must use a coast angle as the independent variable. The procedure for obtaining the time-dependent partials is given below.

We begin with the angle-dependent partials that are used in the original version of PRESTO. One can write (see page 8-21 in PRESTO manual)

$$\delta x_2 \Big|_{\beta_c} = \frac{\partial x_2}{\partial x_1}\Big|_{\beta_c} \delta x_1 \tag{1}$$

The subscript β_c indicates that δx_2 and $\frac{\partial x_2}{\partial x_1}$ are evaluated over a fixed coast angle. δx_2 after a fixed coast time can be written as

$$\delta x_2 \Big|_{t_c} = \delta x_2 \Big|_{\beta_c} - \dot{x}_2 \, \delta t_c \tag{2}$$

where $\dot{x}_2$ is the time rate of change of the trajectory variable at the end of the coast and δt_c is the change in coast time over a fixed coast angle.

δt_c can be expressed as

$$\delta t_c = \frac{\partial t_c}{\partial x_1}^T \delta x_1 \qquad (3)$$

Substituting (2) and (3) into (1), one obtains

$$\delta x_2 \Big|_{t_c} = \left[\frac{\partial x_2}{\partial x_1}\Big|_{\beta_c} - \dot{x}_2 \frac{\partial t_c}{\partial x_1}^T \right] \delta x_1 \qquad (4)$$

The time-dependent matrix of partial derivatives is then

$$\frac{\partial x_2}{\partial x_1}\Big|_{t_c} = \frac{\partial x_2}{\partial x_1}\Big|_{\beta_c} - \dot{x}_2 \frac{\partial t_c}{\partial x_1}^T \qquad (5)$$

Equation (5) is computed in the COAST subroutine. $\frac{\partial x_2}{\partial x_1}\Big|_{\beta_c}$ is computed as before but is now stored in a matrix called PARTL. $\frac{\partial t_c}{\partial x_1}$ is computed as before and is stored in the vector PTC. $\dot{x}_2$ is the appropriate column of the P matrix. After evaluating Eq. (5), $\frac{\partial x_2}{\partial x_1}\Big|_{t_c}$ is stored in PARTL. The adjoint variables at the start of the coast are then evaluated from the equation

$$\lambda_1 = \lambda_2 \frac{\partial x_2}{\partial x_1}\Big|_{t_c} \qquad (6)$$

The equations for time from pericenter, flight path angle, and radius have been changed to eliminate numerical difficulties. The new equations are given on the following page.

Time from Pericenter

$$TZETA = M \cdot (PERIOD)/2\pi \qquad (7)$$

where M is the mean anomaly defined by

$$M = E' - e \sin E'$$

E' is the eccentric anomaly defined by

$$\tan\left(\frac{E'}{2}\right) = \left(\frac{1-e}{1+e}\right)^{\frac{1}{2}} \tan\left(\frac{ZETA\ 2}{2}\right)$$

e is the eccentricity defined by

$$e = \left\{ (1-\lambda_t)^2 + \lambda_r \lambda_t \right\}^{\frac{1}{2}}$$

where $\lambda_t = (V_I \sin \gamma_I)^2 \, r/\mu$

$\lambda_r = H \, V_I \cos \gamma_I \, / \, \mu$

Flight Path Angle

$$\tan \gamma_{I_2} = e \sin (ZETA\ 2)/(1+e \cos (ZETA\ 2)) \qquad (8)$$

Radius

$$r_2 = r_p \, (1+e)/(1+e \cos (ZETA\ 2)) \qquad (9)$$

An iterative procedure is used to find the coast angle that corresponds to the correct time. This is done in the COAST subroutine at statement number 2512. This is the same calculation that previously was done only when the total time constraint was being used. On the initial nominal trajectory, no iteration is done. The initial coast time is determined by the input coast angle.

A line of output has been placed inside the iterative loop. Coast time, coast time error, and coast angle are printed out.

Several changes have been made in the TRAJ subroutine. The DTAU corresponding to an adjustable coast is now a time rather than an angle. The first estimate of the correct coast angle change, DBETAC, is obtained from the equation

$$\mathrm{DBETAC} = \left(\mathrm{DTAU} - \frac{\partial t_c}{\partial V_1}\,\delta V_1 - \frac{\partial t_c}{\partial \gamma_1}\,\delta\gamma_1 - \delta r\frac{\partial t_c}{\partial r_1}\right) \Bigg/ \frac{\partial t_c}{\partial \beta_c} \qquad (10)$$

In addition, a column of the P matrix is computed for each coast stage regardless of whether the coast is adjustable. Finally, it is no longer necessary to divide P by the angular rate when a closed-form coast is used.

One input change is required. The weighting function for all coasts is now the one recommended for the integrated coast, i.e., 10^{-5}.

MISCELLANEOUS CHANGES

1. The burn time is now free during guidance runs. Previously, the weighting function for the adjustable burns was set to a large number during guidance so that no burn time change occurred. This change, together with the switch from angle to time as the independent variable of the coast stage, has resulted in a great improvement in the operation of the intermediate radius-of-perigee constraint. However, for those cases where the optimum coast approaches a circular orbit (lunar and interplanetary transfers, for example), the

radius-of-perigee constraint still fails. The circular park orbit option should still be used for these cases.

2. The equation for cos ϕ in the PCAL subroutine has been multiplied by (sgn η). This will permit the lift force to point down when α is negative.

3. The cos ϕ appearing in the final term of the equation for $\frac{\partial H}{\partial r}$ has been removed.

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